SOCIAL SCIENCES

Women's connectivity in extreme networks

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A popular stereotype is that women will play more minor roles than men as environments become more dangerous and aggressive. Our analysis of new longitudinal data sets from offline and online operational networks [for example, ISIS (Islamic State)] shows that although men dominate numerically, women emerge with superior network connectivity that can benefit the underlying system's robustness and survival. Our observations suggest new female-centric approaches that could be used to affect such networks. They also raise questions about how individual contributions in high-pressure systems are evaluated.

INTRODUCTION

Males are overrepresented within terrorist groups (1). Although examples of famous and historically important female terrorists exist (2, 3), there is still a common tendency to assume that women in general will play more minor, subservient roles than men in terrorist groups that personify highly dangerous and aggressive environments. Indeed, current discourse tends to assume that female ISIS (Islamic State) recruits are "lured," whereas males are "recruited" (4). Such assumptions, influenced by long-standing cultural and societal norms, come at the expense of attempting to understand terrorist behavior and the immediate operational context in which it plays out. This paper typifies the latter approach by conducting a series of social network analyses to test how important women are within such extreme networks despite any numerical and perceived physical disadvantage.

Using new data sets that we have assembled at the highest available temporal resolutions, the results indicate that women tend to be key players in both high-profile online and offline settings. For the online setting, we analyze individuals on the global social media outlet VKontakte (www.vk.com) who become linked when they decide to follow the same online pro-ISIS group page (see Materials and Methods). For the offline setting, we consider time-resolved data (5, 6) concerning the Provisional Irish Republican Army (PIRA) (5–13) covering three decades from 1970 to 1998, where individuals become linked when they decide to collaborate on planning and executing an attack. Although men dominated numerically in each case, we find that women emerge with superior network connectivity at the collective level that is associated with benefits for system robustness and survival (14, 15). The networks that we analyze were not cherry-picked: In addition to being the only such operational networks for which detailed longitudinal information is known concerning the links and nodes over time, they are also the most successful examples for each genre (5–13, 16). Moreover, the network links reflect operational behavior over time, not simple social acquaintance, which means that our results are not clouded by potential differences between women and men in terms of numbers of friends.

RESULTS

Online pro-ISIS network

Figure 1 summarizes our findings from analyzing the online network of ISIS support. To date, ISIS is the most successful example in terms of attracting attention online; its status as the number one terrorist organization is arguably based on its online ability to gather support and spread fear globally (16). Although many millions of online users may casually mention ISIS activity in passing on social media such as Twitter and Facebook, for example, following a recent piece of news, our focus is on the social network of those who share and promote pro-ISIS operational materials, including videos of beheadings, to make a meaningful comparison with the operational offline network of PIRA. Intensive online manual searching in which we trace such narratives and material (see Materials and Methods) revealed that such followers congregate around online group pages of non-U.S. Facebook equivalents, in particular VKontakte. Facebook shuts down such pro-ISIS activity immediately, whereas these online pages manage to grow on VKontakte and become disabled only sporadically. Figure 1A illustrates daily snapshots of a subset of this pro-ISIS network in which individuals are shown as connected if they belong to the same online group page on that given day.

Figure 1B shows the betweenness centrality (BC) for this pro-ISIS network on a daily basis. Materials and Methods indicates the standard definition of BC that we use, whereas fig. S1 demonstrates the meaning of BC and its calculation. The average BC for the women consistently peaks much higher than that for the men (red versus blue spikes in Fig. 1B). Such a high BC can bring global benefits to the network because the BC of a node measures the fraction of shortest paths from all nodes to all others that pass through that given node. Shortest paths between members in covert networks are considered crucial for passing items between any two nodes, because every extra step represents extra risk and potential cost (17–20). Hence, the high average BC for women suggests that women can, on average, play a more central role in passing items such as recruitment messages, files, prayers, and video and audio propaganda; brokering distant parts of the

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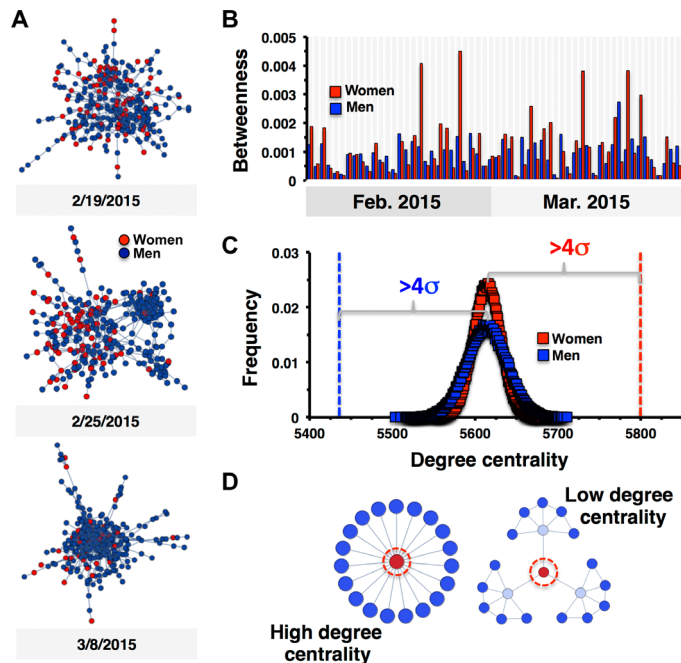*Corresponding author. Email: wuchty@cs.miami.edu

Fig. 1. Online extreme network under pressure (ISIS). (**A**) Illustrative, time-resolved snapshots of a subset of the global online pro-ISIS network on VKontake.com (www.vk.com). Over a 2-month period in early 2015, we observed 16,931 females and 24,883 males. (**B**) Female versus male average BCs over time. Women show frequent large peaks (red) as compared to men (blue). (**C**) Female versus male degree centralities averaged over time. The women's value is more than 4 SDs σ (that is, $Z > 4$) larger than the mean null model result obtained by randomly shuffling node genders, and much larger than the men's value. The opposite is true for men. (**D**) Left: The central node has high BC and high degree centrality. Peripheral nodes have low values of each. Right: The central node has high BC but low degree centrality.

network (for example, aligning narratives); and channeling funds. This importance of high BC was recently noted by Roberts and Everton (*18*), who state that intelligence officers in northern Iraq successfully identified "… actors in an insurgent network who scored high in terms of betweenness centrality (BC) as information insertion points. The effort was … successful in rolling up the insurgency." However, gender-specific roles were not accounted for in that study.

Degree centrality (see Materials and Methods for definition) shows strong daily fluctuations as we might expect: Individuals whose degree centrality becomes high on a given day suddenly have more direct connections and thus become more noticeable to opposing agencies, thereby providing an incentive to rectify this in subsequent days. Despite this, we find that women also achieve a significantly higher average degree centrality than men (red versus blue vertical line in Fig. 1C) and that the women's value is significantly higher than that of a null model where we randomly shuffle the gender of nodes in the underlying time-averaged network (bell-shaped curves in Fig. 1C). The Z score of the degree centrality of men is −4.7, whereas that of women is 4.7. On days when women show higher BC than men, women do not necessarily have a higher degree centrality than men. The net result is that women effectively avoided being noticeable "stars" (Fig. 1D, left) while simultaneously providing the global network benefits of high BC (Fig. 1D, right).

Offline PIRA network

Figure 2 summarizes our findings for PIRA, whose operations were entirely offline during the active period. Not only did PIRA manage to survive a remarkably long period opposing a technologically advanced enemy (UK). It is also regarded as the most successful terrorist network in history in terms of innovating and implementing improvised explosive devices (IEDs) (*5–13*). Starting as an army-like structure, PIRA effectively reorganized itself over a period of a few years between the end of the 1970s and the start of the 1980s, forming a collection of dynamic, self-organized, bottom-up operational units with significant autonomy (*5–13*). We constructed time-resolved networks for each year in the subsequent period from the early 1980s onward, with a link connecting any two individuals involved in the same IED event during that year.

Figure 2A illustrates that the evolution of this PIRA network is accompanied by a marked increase in the number of IED events over this period (Fig. 2B). This evolution culminated in the 1990's peace process. The increase in activity (Fig. 2B) is not accompanied by an increase in available actors (fig. S2). The number of actors appears to decrease, thereby contradicting the simplistic argument that an increase in productivity of such a terrorist organization results from an increase in its size. Compared to ISIS, the PIRA network is small because of the low number of PIRA actors, which is not surprising given that PIRA was an on-street operation whose individuals were targeted by security forces and imprisoned, or killed by opposing paramilitary groups. Such threats also extended to their families and children, strongly motivating PIRA members to remain "under the radar." Despite being a small minority in PIRA, the average BC of women increases over time to values well above those of men (Fig. 2C), whereas their average degree centrality (Fig. 2D) decreases faster than that of men. Although we cannot prove conscious intent in either case, the fact that the risks of on-street PIRA activity are much more direct than those of online ISIS activity offers an explanation as to why PIRA women might have wanted to reduce their average degree centrality over time (Fig. 2D), whereas pro-ISIS women maintained theirs. A full description of PIRA's network evolution and women's involvement undoubtedly requires many additional sociological factors. In Fig. 2E, we momentarily suspend such concerns, adopting instead one possible implication of women's high BC to see what this helps predict about other PIRA network features. Given that high BC is associated with more shortest paths and hence better passing of materials and brokerage, we will momentarily assume that individuals with high BC (that is, women) are more inclined to act as team players than those with lower BC (that is, men). We will also assume that women then spread this team ethic to other individuals in network clusters within which these women sit (see fig. S3 for details). We set this spreading process running on the back of a model of fission-fusion dynamics that was proposed, with empirical support, to describe the internal dynamics in terrorist organizations (*21–24*). This simulation of a network is necessary because we only have PIRA network data on a yearly scale, whereas such spreading likely happens on the scale of weeks or months. Although obviously massively oversimplified, this setup is at least consistent with the fact that a team ethic was known to have spread within PIRA after reorganization. Running this computer simulation
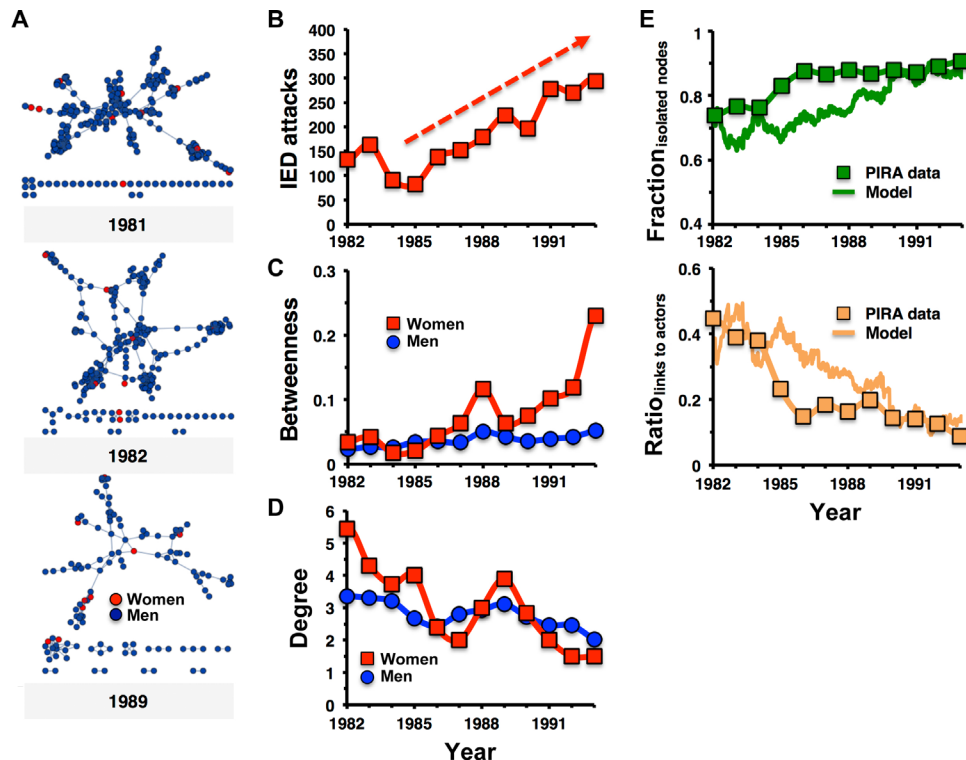
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Fig. 2. Offline extreme network under pressure (PIRA). (**A**) Illustrative, time-resolved snapshots of a subset of the PIRA network following its self-organized restructuring between the end of the 1970s and the beginning of the 1980s. (**B**) Starting from the early 1980s, PIRA's productivity increases in terms of attacks with IEDs. (**C**) Similar increase in BC of women over the same period. (**D**) Degree centrality over the same period. (**E**) Results of a generative model (see fig. S3) showing good agreement with the empirical data for the PIRA network, for the fraction of isolated agents (top) and average number of links per agent (bottom).

yields results that are indeed close to the empirical data for the PIRA network evolution (Fig. 2E).

Association with longevity

Online pro-ISIS groups on VKontakte are sporadically shut down by external agents (25, 26). One might ask whether the presence of women in such online groups has any bearing on that group's longevity. In Fig. 3A, we observe that the longevity of an online pro-ISIS group does indeed tend to increase with the fraction of women that are in it. Turning to the offline PIRA, Fig. 3B draws a related conclusion concerning additional longevity associated with women: Women's connections in the PIRA network have superior longevity to men's and are also superior to a null model where we randomly shuffle members' gender. Such a result is consistent with women's tendency to be better embedded in the network.

DISCUSSION

In our analysis of these offline and online networks, we observed that the topological role of women can differ significantly from that of men. In particular, we observed that the BC of women in both types of network could reach much higher values than that of men. Although further studies of other networks are desirable, our findings suggest that female-centric approaches can be adopted to affect or reengineer extreme networks, even when women are in a minority, by focusing on

women's interconnectivity. By contrast, traditional approaches focus on targeting individual members (invariably men) who may act as hubs (highest degree centrality). More generally, our work raises questions about who the important members are for the development of a network and whether the individual contributions of potentially underrepresented members would be better evaluated in terms of a collective network measure (for example, BC) instead of a local one (degree centrality of individual stars; that is, hubs) (27). We stress that in no way are we suggesting any sort of targeting of women with high BC; instead, our results led us to believe that an effective strategy for reengineering or affecting a network would be to engage with these women.

One limitation of our study is the fact that despite the closure that we achieved during data collection, we cannot prove that our networks are complete. At the very least, however, they are likely representative. Second, a myriad of external events can help shape network evolution. However, uncorrelated noise is unlikely to add additional structure to the network measures upon which we focus (for example, BC). Third, one might wonder if the emergence of women in such key positions in these networks is a consequence of their "exceptional" status. For our ISIS data, the percentage of women followers can reach 50%, ruling out the argument of rarity as a driver. Moreover, available demographic information of highly central individual women does not indicate any features that are statistically different from their male counterparts. Furthermore, the frequency distribution of women's BC has a broad distribution that contradicts the notion of "exceptionality" of a few individuals
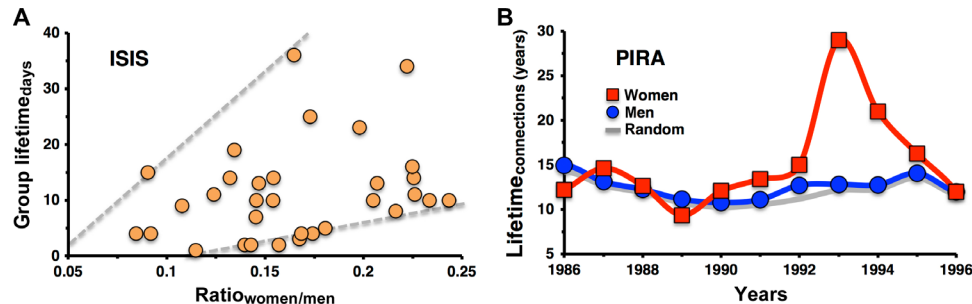
Fig. 3. Lifetime of groups and neighbors in the network. (A) For a larger ratio of women to men in a pro-ISIS online group, we observe, on average, an increase in the group's lifetime (Pearson's $r = 0.28$, $P < 0.1$). **(B)** We observe that PIRA actors directly connected to women have a longer average lifetime as compared to actors directly connected to men. Larger values for women are statistically significant as compared to a null model that randomly shuffles the gender of PIRA members.

(see fig. S4). For the PIRA case, we were able to test the exceptionality hypothesis by comparing the actual list of highest-ranked individuals to lists of candidate women produced independently by several subject matter experts based on the reputation of individual women. There was no correlation—notably, none of the highest-ranking women were those whose reputation was deemed highest by the experts. Fourth, one might wonder whether the central role of women in the PIRA network is the consequence of them monopolizing, or being assigned to, certain operational roles. Because our PIRA data captured demographic and operational information of every PIRA member, we were able to investigate BC as a function of operational role. Figure S5 indicates that there is no clear evidence of network position being tied to a specific operational role. Fifth, we have only discussed here two measures of a social network: BC and degree centrality. However, these measures are standard ones for social networks (17). Although higher-order measures (that is, multinode correlation functions) may, in principle, reveal more detail, the measures that we calculate and their behaviors are real effects. Furthermore, one has to be careful with pursuing increasing detail from such higher-order statistical moments, because they generally require larger amounts of data to give reliable results and are more prone to noise. Sixth, it may happen that the women on online platforms that are dominated by men will naturally attract more attention. However, Fig. 3A suggests that the increased lifetime of a group is actually associated with having more women, which, by that argument, would make the group more noticeable, hence more likely to be shut down, and thus have a shorter lifetime in contrast to the empirical data in Fig. 3A. Finally, we note that we have purposely avoided discussing how our findings might fit into wider debates concerning gender issues in society (28–33) because the present paper is focused on—and limited to—terrorist support online and offline. However, we hope that our findings might one day be incorporated into such wider discourse.

Our results do feed into a growing literature on the importance of centrality in networks that benefits communications, transmission of items, and brokerage (17–20). In their landmark paper, Everton and Cunningham (20) specifically chose BC and degree centrality as measures that are considered important for communication in an extreme network. Their studies of real covert networks, but in another context and without focusing on gender as we do, show that "…the network became increasingly more reliant on a handful of individuals for the brokerage of information and other resources as time went by." It is also known [for example, Kenney et al. (12)] that non-Western covert

networks develop flatter structures akin to PIRA; hence, our results are of more general interest, in particular given that followers of any current or future extremist organization are likely to share files containing propaganda online and hence stand to benefit from high numbers of pathways and high BC (27). It is already known that this passing of material is an essential part of ISIS spreading its message quickly to a broad audience, with audio lectures being circulated by prominent sheikhs (leaders of a Muslim organization or group, or preachers), in addition to prayers, ISIS official videos, links to other sites where the information is shared, and religious books. Such pathways also serve to channel funds and organize the prayer ("dua") for the fighters.

Perhaps most importantly, our work feeds into current discussions about the role of women combatants in conflict and terrorism, and how this can differ from stereotypes in which women adopt a more minor role. In particular, Cohen (34) has explored how women in some African conflicts have been as bloodthirsty or violent as men—and in some cases even more so. Bloom (2) has shown that women can indeed be the source of radicalization in terrorist movements, whereas Sjoberg and Gentry (35) have shown that militarized women have incentives to overcompensate and be more aggressive. Concerning ISIS, our study focuses on women's activity in the online world; however, it would be fascinating to relate this to actual women fighters within ISIS as studied, for example, by Saltman and Smith (36) and Bloom and Winter (37, 38). In addition, it would be interesting to quantify how specific changes in pressure change the centrality of women, and how women's participation transfers across generations within a given family.

MATERIALS AND METHODS

Experimental design
We collected and analyzed the social network structure in two sets of longitudinal data with information about gender of participants.

Online pro-ISIS. Our collection of this data set used both manual and computer-based techniques. We chose VKontakte (www.vk.com) for our pro-ISIS analysis because (i) pro-ISIS group pages are shut down essentially immediately on Facebook, but not on VKontakte; (ii) it allows multiple languages and is used worldwide; (iii) it is the largest European online social networking service with more than 360 million users; (iv) it has been used by ISIS to spread propaganda within the Russian-speaking population (27); and (v) being based in Russia,

it has a high concentration of users of Chechen origin focused in the Caucasus region near ISIS's main area of influence in the Levant. Our methodology for identifying the online pro-ISIS social network was as follows: (Step 1) We manually identified relevant narratives using hashtags across multiple languages, for example, #игиш (that is, ISIS), #дауля (that is, *dawla*, meaning "state"), #халифат (that is, "caliphate"), and #isn #khilafah #fisyria, and traced these to underlying group pages, for example, *fi sabilillah_x*. Relevant group pages were selected on the basis of the observation that they explicitly expressed support for ISIS by publishing ISIS-related news/propaganda and/or their messages contained called for jihad in Syria (Sham). (Step 2) This list was fed into the Application Programming Interfaces software that expanded it using automated search snowballing. (Step 3) The expanded aggregate list was cross-checked to eliminate false identifications. (Step 4) New embedded links were manually searched to identify more group pages and hashtags. (Step 5) We then iterated this process until closure when no new group pages could be found. Although the process was labor-intensive, we were able to find closure on a daily basis in real time. The individual members (followers) of these group pages were then extracted, with these becoming nodes in the social network that we analyze in this paper. On any given day, a link was added between any two individuals who were following the same group page on that day. In this way, we obtained a social network of individuals for each day. The nodes in this network changed in number and identity over time, with some persisting more than others, whereas the links also changed in total number and location in the network. The total number of individuals obtained within the two typical months used for the study (early 2015) was 41,880, comprising 24,883 men, 16,931 women, and 66 with no declared gender. The number of groups was 170. The mean number of followers per group was 624, with a maximum of 8155. The resulting social network had more than a million aggregated links. These results were reproduced for other choices of months during January to May 2015, which is a period during which pro-ISIS support had significant Web presence on VKontakte.

Offline PIRA. This data set, which is widely regarded as the most complete data set of a terrorist organization currently in existence, emerged as part of a 30-month project carried out by researchers at Pennsylvania State University, along with partners at the State University of New York in Albany (5, 6), and included the direct involvement of several co-authors on this paper. It started as a pilot project, in which members of the team built a manual social network by collecting all PIRA members named in the book *Bandit Country* (8), which provides an essentially complete history of the South Armagh Brigade. Following the network ties mentioned there, more individuals were added to the PIRA network, and each individual was characterized with available demographic information. As an expansive step, sifting through all key seminal texts and PIRA statements then produced additional names. After adding their demographic information, more individuals were added through their mentioned ties until a point of self-consistency, and hence closure, was reached. PIRA time-resolved events (5461) involving IEDs were collected, as well as all fatal PIRA shootings. Different IED types were accounted for, for example, letter bombs, pipe bombs, grenades, homemade bombs, static munitions, buried IEDs, undervehicle IEDs, car bombs, mortars, and rockets. Then, the number of complex IED events was tallied, with each such event defined as occasions where an IED was used in conjunction with other types of violent events such as machine gun or sniper fire. Although information about the type of IED event was not specifically used in

this paper, this high resolution helped ensure that events were not missed or double-counted. The data were collected through a mixture of LexisNexis and Irish Times archival stories. Involved individuals could be cross-checked from a number of open sources, such as (i) statements by PIRA including their annual Roll of Honor, (ii) the Belfast Graves publication that offers an account of Republicans killed in combat, (iii) the McKittrick *et al.* study (*10*), and (iv) historical accounts of PIRA from academic sources. Names that were involved in such violent acts were subsequently coded for across a number of sociodemographic, operational, and network variables using the Irish Times archives. Each piece of data (IED event and PIRA militant) was coded twice by separate coders and cross-checked for validity. Similar to many quantitative studies of terrorism and political violence, a number of data constraints exist in this study. However, after an 18-month data collection effort across multiple data sources, this data set is widely considered the best data available. To construct time-resolved networks, we then used these data to create a link between any two actors when they collaborated on the development of an IED and/or planned or executed an assault during a given time period (for example, year). In total, 926 different individuals emerged over time, of whom approximately 5% were women. There was significant turnover in membership of the resulting IED network on a yearly basis, in part due to deaths or imprisonments, but on average, there were 135 men and 6 women per year from 1970 to 1998. Their roles are scattered across the category types, as explained in the references concerning these data and their analysis that we provide in the main paper. The total number of registered members of PIRA was 1382, with 1312 men and 70 women. An in-depth discussion of women of PIRA in this time frame is provided in Bloom's work (*2, 3*) as well as in the work of other researchers (*5–13*).

Statistical analysis

The definition of BC of a node v in a network with a given total number of nodes is given by

$$c_B(v) = \sum_{s \neq t \neq v} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{1}$$

where σ_{st} is the number of shortest paths between nodes s and t, whereas $\sigma_{st}(v)$ is the number of these shortest paths that run through node v. Because the total number of nodes in the connected network changes considerably over time, and we were interested in measuring how BC changes over time, we normalized this quantity in the standard way

$$\overline{c_B(v)} = \frac{c_B(v)}{(N-1)(N-2)} \tag{2}$$

where N is the number of nodes in the connected network at any particular time step [the so-called giant component (*17*)]. Our null model results throughout the paper were obtained by randomly shuffling node genders and then repeating the calculations. We note that although some online individuals might declare incorrect genders, there is no clear incentive to do so because there is no need for individuals to explicitly declare any gender at all. Hence, we expect that this effect does not significantly alter our main conclusions. Indeed, one could argue that incorrect declarations of gender might a priori come from men and women in roughly similar proportions. In support of this, we note that undeclared individuals make up ~0.15% of all users and the degree

centrality of these undeclared individuals is statistically indistinguishable from the null model results ($Z = -0.3$) in Fig. 1C. This implies that the subset of undeclared individuals has a similar statistics to a randomized version of the entire set of online pro-ISIS individuals in which the gender of nodes has been shuffled. This suggests that the decision to not declare genders is not strongly gender-specific. Given this, we suspect that the decision to declare the opposite gender is also not strongly gender-specific and instead acts as a noise term that should not affect our main results.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/6/e1501742/DC1

fig. S1. Importance of BC in a network such as pro-ISIS or PIRA.
fig. S2. PIRA productivity not associated with an increase in the number of PIRA actors.
fig. S3. Schematic of our generative multiagent model.
fig. S4. Evidence that the results of high BC are not a consequence of a few exceptional women.
fig. S5. BC broken down by particular operational roles.

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